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Research Article

The Impact of Coastal Forest Ecosystems on the Hydrochemical Characteristics of Svēte River and its Tributaries under Anthropogenic Load: A Year-Long Assessment

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ABSTRACT

The aim of the research was to assess the impact of coastal forest ecosystems on the hydrochemical characteristics of the Svēte River and its tributaries. The methodology involved year-long monitoring at 16 sites with monthly water sampling and laboratory analysis of physicochemical parameters. The results revealed a pronounced seasonal pattern of nitrogen concentrations, with maximum values during the winter-spring period (up to 14.0 mg/L) and minimum values in summer (around 1.0 mg/L). Phosphorus concentrations showed high spatial variability, with extreme peaks of up to 43.0 mg/L in the estuarine zone and background levels ranging from 0.02 to 0.2 mg/L. Riparian buffer zones wider than 15 m with continuous forest cover reduced nitrogen and phosphorus concentrations by 61% and 76%, respectively, compared with sites lacking buffer vegetation. Stability of the acid-base balance (pH 7.0-8.2) and dissolved oxygen content (8-12 mg/L) was observed, along with the absence of excessive heavy metal concentrations. These findings demonstrate the effectiveness of coastal forest ecosystems in mitigating agricultural nutrient inputs and support their application in river basin water quality management and buffer zone restoration.

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1. INTRODUCTION

The hydrochemical regime of river systems is shaped by the complex interaction between natural processes and anthropogenic factors. Coastal forest ecosystems play an important role in this process by performing buffer functions, regulating the flow of nutrients, organic carbon, trace elements and pollutants, as well as maintaining the stability of hydroecosystems. Under conditions of increasing anthropogenic pressure primarily associated with agricultural land use, urbanisation and forestry activities, the role of riparian buffer mechanisms has become increasingly important. Coastal forests not only reduce the risk of eutrophication in water bodies but also contribute to stabilising the hydrological regime, thereby supporting the ecological status of freshwater systems, particularly in agricultural catchments where nutrient enrichment is a major pressure on surface waters (Devlin & Brodie, 2023; Fedoniuk et al., 2021; Shahini et al., 2025). However, the scale and effectiveness of their impact can vary considerably depending on geographical conditions, the spatial structure of landscapes and the nature of anthropogenic pressures.

A number of studies have demonstrated that riparian vegetation directly influences water quality in small rivers, shaping both local and regional patterns. The study by Saklaurs et al. (2022) confirmed that riparian ecosystems in Latvia play a key role in reducing nutrient content and improving water quality in small watercourses, highlighting the importance of buffer width for nitrate and phosphate removal. The work of Kļaviņa et al. (2021) showed that forestry practices can alter the balance of carbon and nutrients in small catchments, with intensive logging temporarily increasing nitrogen and phosphorus leaching. The research of Pentjuša et al. (2024) further demonstrated that vegetation structure and species composition significantly affect the efficiency of riparian buffer functions. At the catchment scale, diffuse agricultural nutrient inputs have been identified as a dominant driver of hydrochemical variability in European river systems, yet their interaction with riparian buffer structures remains context-dependent and insufficiently constrained (Kirschke et al., 2019; Diegtiar et al., 2020; Prajapati et al., 2025). Despite significant progress, the quantitative influence of coastal forest ecosystems on the hydrochemical parameters of river systems exposed to intensive anthropogenic pressure remains insufficiently studied. This research combines year-long, site-specific hydrochemical monitoring with a systematic classification of riparian forest buffer zones to quantify their effectiveness at the catchment scale. The novelty of the study lies in the integrated examination of seasonal nutrient dynamics, buffer zone attributes, and diffuse agricultural impacts within a transboundary river system, providing empirical evidence linking riparian forest structure to hydrochemical responses under real-world anthropogenic pressure.

The aim of this work was to conduct a comprehensive investigation of the influence of coastal forest ecosystems on the hydrochemical characteristics of the Svēte River and its tributaries under conditions of anthropogenic load. The objectives of the study were to (i) assess the spatiotemporal dynamics of key hydrochemical parameters along the river continuum and (ii) determine the effectiveness of riparian forest buffer zones in mitigating agricultural impacts.

2. METHODOLOGY

2.1. Study Area

The study was conducted within the Svēte River basin, located in southern Latvia, with its headwaters extending into northern Lithuania. Sixteen water quality monitoring points were selected for the study, distributed along the main channel of Svēte River and at the mouths of key tributaries (Figure 1). When determining the locations of these points, information from the Register of Polluted and Potentially Polluted Sites of the Latvian Centre for Environmental Protection, Geology and Meteorology was utilised. This approach enabled the development of a monitoring design that captures not only natural characteristics but also areas of known or potential pollution. The Svēte River basin is characterised by a temperate humid climate typical of the Baltic region, with pronounced seasonality in temperature and precipitation. Hydrological conditions are dominated by snowmelt-driven high flows in late winter and early spring, followed by lower and more stable discharge during summer and early autumn. This seasonal discharge pattern plays a key role in controlling nutrient transport, particularly the mobilisation of nitrogen during high-flow periods.

Point 1 is located at the river mouth (confluence with the Lielupe) and provides an integrated characterisation of the entire Svēte River runoff. Points 2-4 are situated downstream, near the confluences with major tributaries (for example, point 3 is located immediately after the confluence with the Bērze River). Point 5 is positioned near the old landfill (“line 6”) to detect potential leachate impacts, while point 6 is located near a road bridge to assess the influence of wastewater from the roadway.

Several points (7, 8, and 9) are located within or immediately downstream of the administrative boundary of the city of Jelgava (along drainage canals and smaller watercourses such as Baložu, Sprēguma and Lielsvēte streets) to monitor urban impacts. Points 10-13 cover the middle reaches of Svēte River and the lower reaches of its tributaries (Jēkabnieki, the area before "Muzikanti", and Uzini). Points 14-16 are situated in the upper part of the basin, including the border area with Lithuania (near Uzini) and smaller tributaries. The coordinates of the studied points are summarised in Table 1.

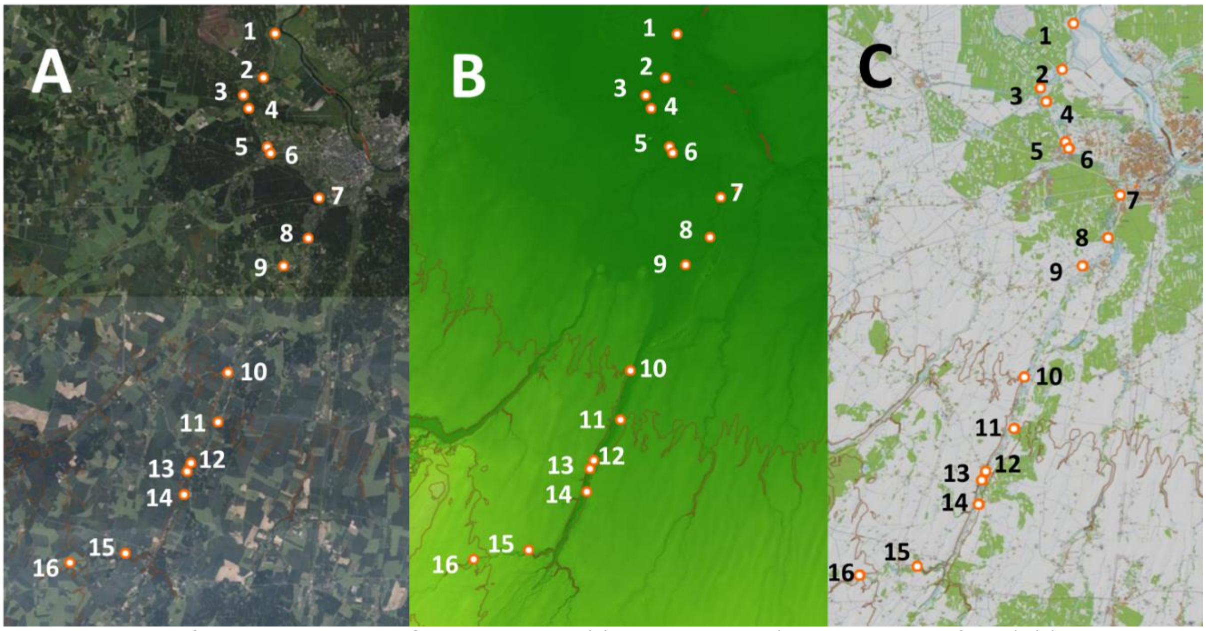

Figure 1. Location of sampling points in the Svēte River basin: (a) satellite imagery (spatial resolution of 10 m); (b) digital elevation model; (c) land use map (white – agricultural land, green – forests, brown – urban areas)

Table 1. Coordinates of water quality monitoring points

No.	Monitoring point name	Coordinates (N)	Coordinates (E)
1	The mouth of the Svēte River at its confluence with the Lielupe River	56.717639	23.643583
2	Warp Bridge	56.693634	23.632929
3	After the confluence of the Berze River	56.684032	23.612682
4	Before the confluence of the Auce River	56.676694	23.618389
5	Polygon "6th line"	56.655769	23.636751
6	Highway bridge (Dobele) over Svēte River	56.652386	23.639978
7	Baložu Street	56.627778	23.688806
8	Spragumah Street	56.605694	23.677639
9	Lelsvēte Street (Svēte district)	56.590584	23.653576
10	Jekabnieki	56.532278	23.598861
11	"In Front of the Musician" area	56.505112	23.589426
12	Uzini	56.482647	23.562527
13	"In front of Uzini" area	56.478005	23.559301
14	Salteni Farm	56.465313	23.55615
15	Kurbuli (between Ziedkalne and Murmuiza)	56.432667	23.498278
16	Tervete/border of Jelgava region	56.427528	23.443917

This monitoring network enabled a comparative analysis of hydrochemical characteristics both along the river (from source to mouth) and between the main channel and its tributaries, helping to identify changes caused by tributary inflows or local land use.

2.2. Sampling and Field Measurements

Water sampling was conducted monthly at each of the 16 points over one year (from January 2019 to December 2019). Samples were collected from the surface layer at a depth of approximately 2-5 cm below the water surface to avoid the ingress of floating particles, oils or films that could distort the results of chemical analysis. During each sampling event, standard in situ measurements of key physicochemical parameters were performed using an AquaProbe AP-7000 multiparameter probe (Great Britain). The calibrated probe was used to measure water temperature, pH, dissolved oxygen (DO), and several inorganic nitrogen compounds: nitrate anion (NO_3^-), nitrite anion (NO_2^-), and ammonium ions (NH_4^+). The device also provided a calculated value of total nitrogen (TN), representing the sum of the measured inorganic nitrogen forms, determined by an integrated sensor. The TN values reported in this study therefore represent the sum of measured inorganic nitrogen species (NO_3^-, NO_2^-, and NH_4^+) as provided by the probe's integrated calculation; organic nitrogen fractions were not included in the TN estimate. In addition, electrical conductivity (as an indicator of the total dissolved solids) and redox potential were recorded. All AquaProbe AP-7000 sensors were calibrated according to the manufacturer's guidelines prior to field deployment. Routine quality assurance procedures included regular calibration checks and inspection of sensor performance to ensure data reliability throughout the monitoring period.

After field measurements, water samples were collected in pre-cleaned (acid-washed and rinsed) polyethylene bottles for subsequent laboratory analysis of nutrient and metal content. To ensure representativeness, samples were taken, whenever possible, from the middle of the stream or from areas with good turbulence. The sample volume for chemical analysis was 500 ml. Preservatives were not used in the field, except for cooling; samples were transported to the laboratory in isothermal containers, and the analysis of major nutrients commenced within 24 hours to minimise biochemical transformations. Water sampling was conducted both within coastal forest areas and open, anthropogenically transformed zones. The use of the AquaProbe AP-7000 multiparameter probe ensured the accurate determination of key hydrochemical parameters characterising the state of the aquatic environment under the influence of natural and anthropogenic factors. Thus, the study addressed both the influence of coastal forest ecosystems on water quality and the magnitude of anthropogenic pressure within the Svēte River basin.

2.3. Assessing the Effectiveness of Buffer Coastal Zones

Several complementary methods were developed and applied to comprehensively assess the effectiveness of the buffer functions of coastal forest ecosystems. All sixteen monitoring points were classified according to three key parameters: the width of the coastal forest strip, the degree of its continuity, and the species composition of vegetation. Riparian buffer zones were classified using a semi-quantitative approach based on these three criteria. Buffer width was measured perpendicular to the riverbed, from the water's edge to the boundary of agricultural land, and categorised as <5 m (narrow), 5-15 m (moderate), and >15 m (wide). Vegetation continuity was assessed visually along the riverbank and classified as discontinuous (<50% continuous cover), partially continuous (50-80%), or continuous (>80%). Vegetation structure was defined based on the dominant cover type, including grassland, mixed shrub-tree vegetation, or closed forest canopy.

A detailed visual assessment was conducted at each point, including the identification of tree-layer species composition, evaluation of the projective cover of the grass layer, assessment of buffer zone disturbance caused by the presence of paths, trampling, or unauthorised dumping, and estimation of undergrowth density. Based on these criteria, all monitoring points were divided into three categories. Category 1 (no buffer zone) included points 5, 6, 7, and 8, where the width of the riparian forest strip was less than 5 metres or entirely absent. Category 2 (moderate buffer zone) comprised points 1, 2, 3, 4, 9, and 10, characterised by a strip width of 5-15 metres and discontinuities in vegetation cover. Category 3 (developed buffer zone) included points 11, 12, 13, 14, 15, and 16, with a width greater than 15 metres and continuous forest cover. For each of the defined categories, the following parameters were examined: TN, total phosphorus (TP), NO_3^-, NH_4^+, and concentrations of suspended solids. A comparative analysis of pollutant reduction efficiency between categories was performed, seasonal dynamics of buffer zone effectiveness were assessed, and the influence of vegetation type on the absorption capacity of each category was analysed.

2.4. Laboratory Analysis

Laboratory analyses were conducted to determine TP and a range of metals and metalloids using inductively coupled plasma optical emission spectrometry (ICP-OES). Prior to analysis, water samples were prepared by acidifying each sample to approximately 1% HNO_3 (by adding ultrapure nitric acid) and allowing them to undergo "acid digestion" for three days. This procedure ensured the transition of metals adsorbed on suspended particles into solution and stabilised the sample matrix. After the digestion period, the samples were filtered through paper filters to remove residual particles. The filtered and acidified samples were then introduced into the ICP-OES system.

The ICP-OES method is based on atomising the sample in a high-temperature plasma, where elements emit light at characteristic wavelengths; measurement of the radiation intensity enables quantification of the concentrations of specific elements. The following elements were analysed: phosphorus (P), arsenic (As), zinc (Zn), copper (Cu), chromium (Cr), manganese (Mn), lead (Pb), vanadium (V), nickel (Ni), aluminium (Al) and iron (Fe). The selection of these elements was guided by the need to include common contaminants heavy metals and toxic metalloids that may originate from agricultural chemicals (for example, phosphate fertilisers, which may contain impurities), industry, motor vehicles, or the natural geochemical background.

The ICP-OES instrument was calibrated using standard solutions for each element, and quality control procedures included the analysis of blanks and spiked samples to ensure measurement accuracy. Method detection limits (LOD) for the analysed elements ranged from 0.2 to 5.0 μg/L, depending on the element, and were below the corresponding European Environmental Quality Standards (EQS) for all regulated metals. Analytical precision, assessed through replicate measurements, was generally within ±5% relative standard deviation. Accuracy was evaluated using spiked samples, with recovery rates typically ranging between 90% and 110%.

2.5. Data Processing

All collected data were systematised and processed to identify spatiotemporal patterns. Time series were constructed for each parameter and sampling point to analyse seasonal trends, while spatial profiles were generated to compare concentrations upstream and downstream during the same sampling period. Basic descriptive statistics (mean, minimum, maximum, and standard deviation) were calculated for key parameters (TN and TP) at each observation point and for the entire dataset. The annual load of TN and TP transported by Svēte River to the Lielupe was calculated. Concentration data from point 1 (river mouth) were combined with water discharge data to estimate the load. Water discharge data were obtained from the nearest hydrological station or estimated based on the discharge of the Lielupe River and catchment area ratios. Multiplying the average monthly concentration by the monthly runoff volume, followed by summation, yielded an estimated annual load. Uncertainty in annual nutrient load estimates was assessed by propagating variability in monthly concentration data. For each month, the mean concentration and its standard deviation were used to derive uncertainty bounds, assuming an approximately normal distribution of concentration values. Annual loads were calculated as the sum of monthly loads, and 95% confidence intervals were estimated based on the cumulative variance of monthly estimates. This approach accounts for temporal variability in concentrations and provides an interval-based representation of annual nutrient export rather than a single point estimate.

Pearson correlation analysis was performed to identify relationships between parameters and to interpret processes (for example, the relationship between DO and nutrient concentrations as evidence of eutrophication, or between conductivity and nitrate to assess the impact of agricultural runoff). Tributary data were also compared to identify sub-basins with consistently elevated pollutant concentrations. Various statistical methods were employed to assess relationships between buffer zone characteristics and water quality, including Pearson correlation analysis, multivariate regression analysis, ANOVA to test differences between buffer zone categories, and cluster analysis to group monitoring points with similar characteristics. To determine seasonal variations in buffer zone effectiveness, data were compared across three periods: the spring flood period (March-April), the summer-autumn period (June-October), and the winter period (November-February). All statistical analyses were performed using R software (version 4.x). Differences were considered statistically significant at $p<0.05$ for all statistical tests.

3. RESULTS AND DISCUSSION

3.1. Variability of Nutrient Concentrations

The monitoring results revealed clear temporal patterns for nitrogen compounds and more sporadic dynamics for phosphorus within Svēte River system. TN concentrations exhibited a pronounced seasonal trend that was consistent across all 16 sampling points. In general, the highest TN levels were observed in late winter and early spring, while the lowest occurred in summer. The peak TN concentration reached 14.0 mg/L (expressed as N) in February, recorded at several points, including those in the lower reaches. During summer (June-August), TN decreased to approximately 1.0 mg/L in most areas, corresponding to the annual minimum. This seasonal amplitude nearly an order of magnitude difference indicates a strong influence of seasonal processes, such as nitrogen leaching from soils during wet and cold periods, and biological uptake during the growing season. Even tributaries with differing land use types demonstrated synchronous winter peaks and summer declines, although their absolute values varied somewhat. Overall, the waters of Svēte River can be classified as nitrogen-enriched during winter (with concentrations occasionally exceeding drinking water standards), whereas in summer they fall to levels typical of unpolluted or slightly polluted watercourses. The pronounced seasonal pattern of TN concentrations is illustrated in Figure 2.

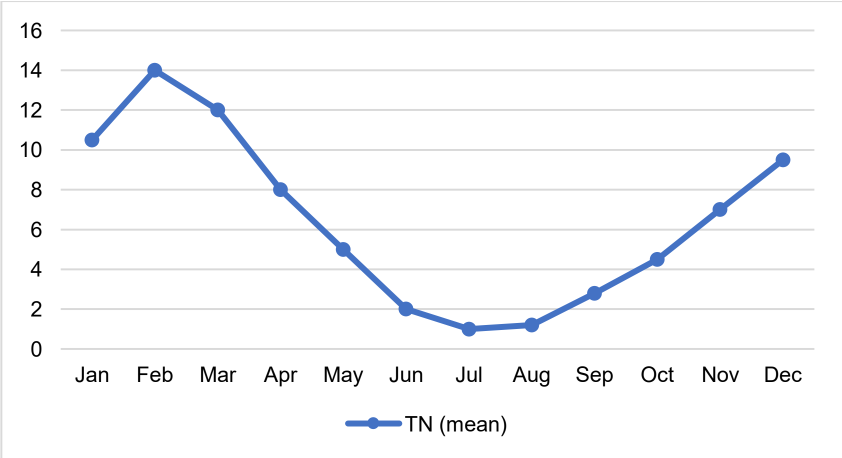

Figure 2. Seasonal dynamics of TN concentrations in the Svēte River system during 2019

As shown in Figure 2, TN concentrations peaked during the late winter and early spring and declined sharply during summer, reaching minimum values in June-August, followed by a gradual increase in autumn. This temporal pattern indicates that nitrogen transport in the Svēte River system is primarily governed by seasonal hydrological processes, with elevated winter and early spring concentrations associated with enhanced leaching from agricultural soils under high-flow conditions. The consistency of this seasonal signal across all monitoring sites suggests a basin-wide response rather than localised point-source effects. In contrast, TP concentrations were highly variable both temporally and spatially. The data did not reveal a consistent seasonal pattern across all points; instead, phosphorus levels appeared to be influenced by localised events and sources. The most notable finding was a TP concentration of 43.0 mg/L recorded in June at point 1 (the river mouth near the Lielupe), which stands out sharply within the dataset and is unusually high for surface waters. This value represents a single episodic observation, for which replicate laboratory analysis was not conducted. Nevertheless, even when interpreted with caution, the occurrence of such an extreme value suggests the possibility of high-magnitude phosphorus pulses in the estuarine zone, which are environmentally relevant even if rare.

By comparison, TP concentrations at other points in June ranged from approximately 0.5 to several mg/L, and at point 1 itself TP levels were significantly lower in other months. The lowest recorded phosphorus concentrations were 0.02 mg/L, observed at point 15 (an upper tributary) in January and May. In many areas, particularly within the upper and middle reaches, TP levels remained within the range of 0.05-0.2 mg/L for most of the year, indicating relatively good water quality with respect to phosphorus (<0.1 mg/L is generally considered low) (Table 2). However, individual peaks occurred sporadically: aside from the major June spike at the mouth, several other points exhibited moderate TP increases in spring or early summer (e.g. point 5 near the landfill showed a rise in April, and point 9 near Lielsvēte in July), though these were an order of magnitude lower than the 43 mg/L recorded at point 1.

Table 2. Summary data on concentrations of TN and TP in Svēte river, 2019

Water quality indicator	Minimum concentration (mg/L)	Maximum concentration (mg/L)
TN	1.0 (June-August, various points)	14.0 (February, several points; peak in w. 3)
TP	0.02 (January and May, w. 15)	43.0 (June, w. 1 – mouth)

As shown in Table 2, the extreme phosphorus value is considerably higher than typical P levels in rivers and even exceeds the concentrations generally found in untreated municipal wastewater. This anomaly indicates a single pollution event or localised source that affected the estuary in June. Since point 1 is located at the confluence, it may have been influenced either by reverse flow from the Lielupe River (which can transport substantial pollutant loads from upstream sources) or by a local discharge, such as a one-off release of livestock waste or fertilisers into the lower Svēte. Excluding this event, the next highest TP values in the dataset were around 1-2 mg/L in the midstream during spring, which, while still elevated, are more consistent with known impacts from agricultural runoff.

Despite these fluctuations, other water quality parameters remained within acceptable limits for most of the observation period. For instance, pH values ranged from approximately 7.0 to 8.2 slightly alkaline, as expected for a river influenced by limestone geology and dissolved oxygen concentrations typically ranged between 8 and 12 mg/L, which is sufficient to support aquatic life except during temporary reductions caused by heatwaves in slow-flowing areas. Electrical conductivity was moderate (400-600 μS cm^{-1}), reflecting dissolved salts derived from soils and possibly some agricultural inputs, but not unusually high. None of the analysed heavy metals were detected at concentrations exceeding Latvian or European freshwater quality standards; measured values were either below detection limits or within the applicable regulatory thresholds. Most metals were either below the detection limit or present at trace levels typical of unpolluted waters (for example, iron occurred at several hundred μg/L, consistent with natural leaching from soils). Even at point 5, located near the landfill, no significantly elevated concentrations of heavy metals were observed, suggesting that the old landfill is not currently a notable source of metal leaching or that any leachate is rapidly diluted. Overall, nutrients (N and P) appeared to be the main parameters of concern, while heavy metal pollution in Svēte River during the study period was low.

3.2. Influence of Tributaries of Svēte River and Spatial Trends

Comparison of upstream and downstream sampling points provided insights into how tributaries influence the chemical composition of the main river. For TN, the results were largely consistent tributaries exhibited high nitrogen content during winter, which collectively resulted in elevated nitrogen levels in River; however, no single tributary caused a distinct increase in concentrations at the confluence beyond what was already present in the main channel. This indicates cumulative diffuse pollution: each sub-basin contributes its share of nitrogen, and due to the predominance of farmland, this contribution is spatially distributed. A slight downstream trend was observed, with background TN concentrations increasing from approximately 2-4 mg/L (annual average) in the upper reaches to about 5-6 mg/L in the lower Svēte. This increase is expected, as the river integrates a progressively larger agricultural area. Notably, the confluence with the Bērze River (point 3) did not cause a sharp change in nitrogen levels, indicating that nitrogen concentrations in the Bērze were comparable to those in Svēte at that time. The Tērvete and Auce rivers (flowing into Svēte near points 4 and 10-12) similarly exhibited nitrogen concentrations consistent with those of the main river. Thus, no “hot spot” of nitrogen input was detected; seasonal cycles were the dominant factor controlling spatial variations in nitrogen.

Phosphorus, however, displayed more pronounced spatial variability. The lowest downstream point (point 1), apart from one extreme value, generally showed greater variation. Point 1 often recorded higher TP concentrations than the next upstream site (point 2, Warpa Bridge) on corresponding dates, suggesting the presence of additional phosphorus sources near the mouth. One possible explanation is the influence of the city of Jelgava (although its wastewater is discharged into the Lielupe rather than the Svēte) or inputs from small settlements and agricultural lands within the floodplain immediately upstream of the confluence. Another possibility is that sedimentation dynamics at the confluence where backflow from the Lielupe may occur cause phosphorus release from sediments under specific conditions, such as anoxia or physical disturbance. Some tributaries also exhibited higher phosphorus concentrations at certain times. The Lielsvēte stream (point 9) recorded TP peaks of about 0.5 mg/L in summer, which may have locally increased TP levels in Svēte at points 8 or 7 downstream of its confluence. The tributary at point 15, located in a forested upper catchment, consistently showed very low phosphorus concentrations (about 0.02-0.04 mg/L), representing the natural background level.

Meanwhile, the Auce River (point 4, before its confluence with Svēte) displayed moderate TP values (~0.1-0.2 mg/L), likely resulting from agricultural activity in its basin, but without excessive discharge. The Bērze River, known to drain agricultural areas and several small towns, contributed episodic phosphorus loads: point 3 (after its confluence) occasionally showed slightly higher TP values than point 10 (Svēte upstream of the confluence), confirming its localised influence. Overall, the tributaries represent important sources of phosphorus, and the heterogeneity of TP between sampling points indicates localised pollution inputs, such as manure application near certain tributaries or one-off discharges from fish ponds or farm wastewater. This spatial analysis helps identify priority areas for intervention for example, improving management practices within the sub-basin feeding point 1, should a specific source of the June incident be confirmed there.

3.3. Annual Nutrient Loads and Water Quality Status

Using the obtained concentration data and estimated water discharges, the annual nutrient export of Svēte River was calculated. It was estimated that approximately 1,100 tonnes of nitrogen and 9 tonnes of phosphorus were transported from Svēte to the Lielupe each year. These figures indicate a substantial nutrient flux for a river of this size. The nitrogen load 1.1 kt N per year from Svēte, a sub-tributary adds to the nutrient burden of the Lielupe River and, ultimately, to the Gulf of Riga in the Baltic Sea. The Baltic Sea is known to experience eutrophication problems, and rivers such as the Lielupe (and consequently Svēte) are recognised sources of nitrogen and phosphorus inputs. The data on elevated winter nitrogen concentrations confirm that a significant portion of the annual nitrogen load is likely delivered during the winter-spring period. The phosphorus load estimate is largely influenced by a single exceptionally high value; excluding this event would result in a lower annual phosphorus load on the order of a few tonnes. Nevertheless, even several tonnes of phosphorus can contribute considerable nutrient inputs to receiving waters for instance, one tonne of phosphorus could theoretically stimulate the growth of approximately 500 tonnes of algal biomass (assuming the Redfield ratio).

With respect to water quality classification, apart from nutrient enrichment, Svēte River can generally be categorised as having “good” chemical status according to typical regulatory criteria. Nutrients remain the primary parameters that could shift its ecological status to moderate or poor if they promote excessive algal proliferation. No visible symptoms of eutrophication were observed during field surveys in the study year; mass algal blooms were not recorded in Svēte, probably due to sufficient flow velocity and shading in certain sections. However, elevated nutrient concentrations pose a potential risk during summer low-flow periods, these nutrients could stimulate algal growth downstream or within the Lielupe. Although metal concentrations were low, trace amounts of elements associated with agrochemical use, such as copper and zinc (commonly present in fertilisers and pig feed additives), were detected. These concentrations remained within safe limits but nonetheless indicate anthropogenic influence. This hydrochemical assessment of Svēte River illustrates how diffuse agricultural pollution drives fluctuations in water quality. The pronounced seasonal variability of TN corresponds with findings from other temperate rivers: winter and early spring are characterised by intensive nitrate leaching from saturated soils, with peaks reaching 14 mg/L TN in February. Comparable winter peaks exceeding 10 mg/L nitrate-N have been documented in Germany and the United Kingdom (Kirschke et al., 2019). Although the value of 14 mg/L TN surpasses the EU drinking water standard (50 mg/L expressed as nitrate), Svēte River water is not used for potable supply. During summer, TN concentrations decline to approximately 1 mg/L, reflecting natural purification processes such as biological uptake, denitrification, and dilution by low-nutrient background runoff. Since these seasonal peaks are primarily a result of land use rather than specific management measures, strategies such as the implementation of cover crops or controlled drainage systems are needed to reduce winter nitrate losses.

Phosphorus (P) transport was more erratic. Although typical TP levels in Svēte are approximately 0.1 mg/L comparable to many European agricultural rivers a sharp spike of 43 mg/L TP was recorded at the river mouth in June, a value far too high to be explained by normal diffuse runoff. This anomaly may reflect a localised manure discharge, surface flow carrying farm waste, or backflow from the Lielupe (which is known for its high organic matter loads), possibly creating “stagnant” conditions. Such episodic events may trigger algal blooms or lead to phosphorus accumulation in sediments, causing internal loading under low-oxygen conditions downstream. Overall, heavy metal concentrations in Svēte were minimal, indicating limited industrial impact. Organic matter remains a major concern, reflecting a broader pan-European trend: as industrial and urban pollution has decreased due to improved treatment, agricultural non-point sources now dominate (Devlin & Brodie, 2023; Kozyatnyk et al., 2017; Sergaliyev et al., 2017). The current estimate of approximately 1.1 kt N and 9 t P discharged annually into the Lielupe and, subsequently, the Gulf of Riga highlights the basin’s contribution to eutrophication. Achieving the objectives of the Baltic Sea Action Plan requires enhanced nutrient management, including precision fertilisation, establishment of buffer zones, construction of artificial wetlands, and improved treatment of rural wastewater (for example, upgrading septic systems or connecting households to centralised facilities).

In summary, Svēte remains relatively healthy, with good oxygen levels and moderate turbidity, indicating its capacity to respond positively to mitigation measures. Continued monitoring can help assess whether interventions such as the use of cover crops or improved fertilisation practices are effective in reducing winter peaks of TN (Toneva & Dimitrova, 2024; Karasheva et al., 2023). Coordination with Lithuania, where part of Svēte headwaters originate, is also essential. As the river crosses national borders, management strategies should likewise be transboundary.

3.4. Assessment of the Effectiveness of the Buffering Functions of Riparian Forest Zones

To evaluate the effectiveness of the buffering role of riparian forest ecosystems, a comparative analysis of hydrochemical parameters was conducted in areas with varying degrees of riparian forest belt preservation. The results of this comparative analysis are presented in Table 3.

Data analysis revealed a clear correlation between the width and quality of riparian forest belts and their effectiveness in reducing pollutant concentrations. Sites with well-developed buffer zones (category 3) exhibited, on average, 61% lower concentrations of TN and 76% lower concentrations of TP compared with sites lacking buffer zones. The most illustrative comparison is between sites 15 and 5, which are located under similar land-use conditions. Site 15 (a forested upper area) consistently recorded low TP concentrations (0.02-0.04 mg/L), whereas site 5 (near the landfill, without a buffer zone) showed significantly higher TP values (0.15-0.35 mg/L) throughout the year. Statistical analysis (ANOVA) confirmed that the differences between categories were significant for all major water quality parameters ($p<0.01$). The Pearson correlation coefficient between buffer zone width and TN concentration was -0.78, and for TP -0.82, indicating a strong inverse relationship. The effectiveness of buffer zones also varied seasonally. The highest efficiency was observed during the spring flood period, when buffer zones retained up to 85% of nutrient runoff from adjacent agricultural land. During the summer period, efficiency decreased slightly to 55-60%, which is associated with reduced surface runoff. Additional analysis showed that the efficiency of buffer zones depends not only on their width but also on vegetation type. Areas with mixed deciduous-coniferous stands demonstrated 15-20% higher efficiency compared with homogeneous coniferous stands, owing to better absorption capacity and a more developed root system. These results confirm the critical role of riparian forest ecosystems in mitigating the anthropogenic impacts of agricultural activity and emphasise the importance of preserving and restoring buffer zones along Svēte River and its tributaries.

Table 3. Effectiveness of buffer zones in reducing pollutant concentrations

Parameter	**Category 1 (none)**	**Category 2 (moderate)**	**Category 3 (developed)**	**Reduction efficiency, %**
TN, mg/L	8.2±3.1	5.8±2.4	3.2±1.8	61%
TP, mg/L	0.38±0.31	0.21±0.18	0.09±0.07	76%
Nitrates (NO_3^-), mg/L	6.8±2.9	4.3±2.1	2.1±1.4	69%
Ammonium (NH_4^+), mg/L	0.42±0.25	0.28±0.16	0.15±0.09	64%
Suspended solids, mg/L	18.5±8.2	11.2±5.3	6.8±3.1	63%

Data are presented as mean ± standard deviation. Sample size (n) refers to site-month observations aggregated for each buffer zone category over the monitoring period.

To assess the seasonal robustness of buffer zone effectiveness, the comparative analysis was additionally examined across the three hydrological periods defined in the study (spring flood, summer-autumn, and winter). The direction of differences between buffer zone categories remained consistent across all seasons, with sites characterised by developed buffer zones (category 3) systematically exhibiting lower concentrations of TN and TP compared with sites lacking buffer vegetation. Although the absolute magnitude of reduction varied seasonally, the relative ranking of buffer zone categories was preserved, indicating that the observed buffer efficiency is not restricted to a single season but represents a stable pattern under varying hydrological conditions.

The results obtained demonstrate a significant impact of agricultural activity on the hydrochemical regime of Svēte River, consistent with findings from numerous international studies. The pronounced seasonal dynamics of nitrogen concentrations, with a peak during the winter-spring period, reflect general patterns characteristic of regions with intensive agriculture. The study by Kirschke et al. (2019) on German water bodies analyses in detail the mechanisms of nitrate leaching from agricultural lands during flood periods, demonstrating the role of winter precipitation in the transport of nitrogen compounds. The authors particularly emphasise the complexity of managing diffuse pollution in large catchment basins. The recorded data on elevated nitrogen concentrations (up to 14.0 mg/L) and sporadic phosphorus peaks (up to 43.0 mg/L) in Svēte River can be regarded as key risk factors for eutrophication, which fully aligns with the conclusions of Devlin and Brodie (2023) regarding the critical role of excess nutrients in triggering eutrophication processes in aquatic ecosystems. The seasonal pattern of nitrogen pollution, with a maximum in the winter-spring period, confirms the general regularities of nutrient transformation in river ecosystems described by Tiwari and Pal (2022).

The interpretation of predominantly diffuse nitrogen inputs is further supported by the spatial land-use structure of the Svēte River basin (Figure 1c), which is characterised by extensive agricultural areas and limited urban development outside the Jelgava zone. The absence of pronounced point-source hotspots along most monitoring reaches, together with the synchronous seasonal TN patterns observed across sites, is consistent with a predominantly diffuse contribution of agricultural runoff and soil leaching, rather than widespread localised point discharges. Comparable basin-scale responses of nutrient concentrations to diffuse agricultural pressures have been reported in other intensively used catchments, underscoring the role of land-use structure in shaping nitrogen dynamics (Bao et al., 2022; Shumka et al., 2020).

Comparable seasonal nitrogen patterns have been reported in agricultural catchments worldwide, confirming the global relevance of diffuse nutrient pollution under intensive land use (Su et al., 2024; Kerimkhulle et al., 2022). In contrast, phosphorus concentrations exhibited substantially higher temporal and spatial variability. Previous studies consistently demonstrate that phosphorus dynamics in agricultural and mixed catchments are highly heterogeneous and strongly controlled by local hydrological conditions, sediment processes, and episodic inputs, rather than by uniform seasonal patterns (Zhang et al., 2022; Zhou et al., 2023). Against this background, the distinguishing feature of the present research is the identification of an exceptionally high phosphorus concentration, which may indicate unique hydrological or localised conditions in the mouth area of the Svēte River.

Several alternative hypotheses may account for the exceptionally high TP concentration recorded at the river mouth. One plausible mechanism is the release of phosphorus from bottom sediments during periods of increased discharge or water-level fluctuations, which can enhance sediment resuspension and the mobilisation of particle-bound phosphorus in estuarine environments. Similar mechanisms of phosphorus mobilisation from bottom sediments have been documented in stormwater and low-flow aquatic systems, where sediment-bound phosphorus may be released during hydrological or physicochemical disturbance events (Lusk & Chapman, 2021; Adekenov & Gafurov, 1992; Hussain et al., 2022). Such processes have been reported for lowland river mouths and are known to generate short-term but pronounced concentration peaks. Another possible explanation relates to hydrodynamic interactions at the confluence with the Lielupe River. Backwater effects, transient flow reversals, or mixing under low-velocity conditions may promote the temporary accumulation of phosphorus-enriched water masses derived either from upstream transport or from adjacent aquatic zones. Such spatial heterogeneity is consistent with the concept of hydrological connectivity, whereby local mixing, backwater effects, and flow reversals at confluences can substantially modify nutrient transport and accumulation patterns (Zhang et al., 2021; Peruzzo et al., 2018; Ben Meftah et al., 2015).

Analytical or sampling uncertainty also cannot be entirely excluded, as the extreme TP value represents a single episodic observation for which replicate laboratory verification was not available. Nonetheless, even when interpreted with caution, the occurrence of a phosphorus pulse of this magnitude is environmentally significant, given that episodic high-concentration inputs can exert a disproportionate influence on eutrophication dynamics in receiving waters. Identifying the precise origin of such episodic contamination remains challenging in river systems, particularly when grab sampling is applied, as demonstrated by contamination source identification studies in complex water networks (Ji et al., 2022; Glevitzky et al., 2025; Merkhatuly et al., 2017). It should also be noted that monthly sampling may underestimate short-lived pollution events, as high-frequency monitoring studies have shown that episodic nutrient pulses can occur over timescales of hours to days (Qi et al., 2020; Kerimkhulle et al., 2023).

The effectiveness of coastal buffer zones revealed in this study is supported by the work of Sibley et al. (2020), who analyse in detail the role of riparian forest ecosystems in maintaining water quality, particularly in agricultural landscapes. The present research demonstrates that even partially degraded riparian ecosystems can substantially reduce pollutant inflow. The study by Xu et al. (2022) provides a quantitative assessment of buffer zone effectiveness in reducing pollutant inputs, which is consistent with the results obtained here. Furthermore, the findings of Liang et al. (2022) confirm the key role of riparian vegetation in preventing soil erosion and reducing nutrient inputs. Thus, buffer zone effectiveness in the Svēte River basin reflects the combined influence of vegetation structure, zone width, and the local hydrological regime. The applied ICP-OES methodology complies with current analytical standards and provides reliable quantification of trace metals in surface waters (Vieira et al., 2024; Kozyatnyk et al., 2015; Yakovkin et al., 1998). The absence of excess concentrations of heavy metals can be compared with the findings of Hwang et al. (2023), who reported substantially higher metal levels in water bodies located within highly urbanised areas. In the present study, measured concentrations of trace metals remained below the EQS for surface waters. Specifically, concentrations of As, Pb, and Ni did not exceed the corresponding EQS values of 10 μg/L, 7.2 μg/L, and 20 μg/L, respectively, as established by Directive 2013/39/EU. Concentrations of Cu, Zn, and Cr were also consistently below applicable regulatory thresholds defined for surface waters, indicating the absence of significant metal contamination.

In general, the chemical status of the Svēte River is shaped primarily by diffuse agricultural pressures, with nutrients representing the main risk factor, while industrial metal contamination remains negligible. The importance of monitoring non-metal pollutants in such settings is highlighted by Saravanan et al. (2023), who emphasise the role of organic contaminants in agricultural pollution contexts. Their analytical approach may be informative for future investigations in the Svēte River basin. Integrated monitoring approaches that combine field measurements with spatial analysis are increasingly recognised as essential for understanding inland water quality dynamics at the catchment scale (Topp et al., 2020), and recent studies indicate that spatial heterogeneity of water quality parameters is often more pronounced during low-flow and dry-season conditions (Yin et al., 2024). The integration of remote sensing techniques with ground-based monitoring further enhances the potential for effective water quality assessment in transboundary catchments (Guerra et al., 2020; Oderiy et al., 2024). In summary, despite regional differences, the processes governing water quality formation in agricultural catchments exhibit consistent patterns, supporting the broader applicability of the present findings under conditions of intensive land use.

4. CONCLUSION

The study provides a detailed description of the hydrochemical state of the Svēte River system, demonstrating how agricultural activities and localised anthropogenic loads alter water quality. During the annual monitoring period, TN concentrations exhibited pronounced seasonal dynamics, with a peak in the winter–spring period and a minimum in summer, indicating high sensitivity of the nitrogen regime to climatic conditions and agricultural land use practices. The obtained data confirm that diffuse sources, particularly fertilised agricultural fields, play the dominant role in elevated nitrogen concentrations. In contrast, TP concentrations were characterised by irregular spikes and the formation of local "hot spots", indicating the influence of localised and episodic factors on phosphorus mobilisation and transport. Although moderate to low phosphorus levels were observed for most of the year, exceptionally high concentrations (e.g., 43 mg/L near the river mouth) suggest short-term inputs associated with point discharges, sediment remobilisation, or hydrodynamic effects at the confluence. Such episodic events underline the need for monitoring capable of capturing short-lived pollution pulses that may remain undetected by standard monthly sampling.

Despite nutrient fluctuations, most other water quality parameters (pH, dissolved oxygen, and trace metals) remained within acceptable limits throughout the study period, indicating that eutrophication driven by nitrogen enrichment and sporadic phosphorus inputs represents the primary environmental risk for the Svēte River. The estimated annual export of approximately 1.1 kt of nitrogen and 9 t of phosphorus highlights the contribution of the Svēte River to nutrient loading of the Lielupe River and ultimately the Baltic Sea. The assessment of riparian buffer zones demonstrated a strong relationship between buffer characteristics and pollutant reduction efficiency. Buffer zones wider than 15 m reduced TN concentrations by an average of 61% and TP concentrations by 76%, while narrower or absent buffers showed substantially lower retention capacity. The highest efficiency was observed during the spring flood period, when buffers retained up to 85% of incoming nutrient loads. Mixed broadleaf-coniferous vegetation was 15-20% more effective than homogeneous coniferous stands. From a management perspective, the results support implementing riparian buffer zones with a minimum width of 15 m along agriculturally influenced river sections, combined with mixed tree and shrub vegetation. Preservation of existing buffers and targeted restoration in priority sub-basins, particularly near the river mouth and major tributary confluences, should be considered key measures for reducing diffuse nutrient pollution. Future research should expand monitoring to include additional pollutant groups and integrate catchment modelling to assess the combined effects of climate change, land use, and mitigation measures, supporting cost-effective strategies for sustainable water quality management in the Svēte River basin and similar agricultural catchments.

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CONFLICT OF INTEREST
The authors declare that there is no conflict of interests.

AUTHOR CONTRIBUTION
Anda Bakute: Conceptualization, Methodology, Investigation, Supervision. Jovita Pilecka-Ulcugaceva: Data Collection, Investigation, Writing Original Draft. Paula Miezaka: Data Collection, Software, Visualization. Kristaps Siltumens: Software, Validation, Formal Analysis. Inga Grinfelde: Writing – Reviewing and Editing, Methodology, Supervision.

DATA AVAILABILITY
The data that support the findings of this study are available on request from the corresponding author.

DECLARATION OF GENERATIVE AI
Not applicable.

ETHICS
Not applicable.

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